Early Planet Formation as a Trigger for further Planet Formation[1]

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Recent discoveries of extrasolar planets[1,2] at small orbital radii, or with significant eccentricities, indicate that interactions between massive planets and the disks of gas and dust from which they formed are vital for determining the final shape of planetary systems[3,4,5,6]. We show that if this interaction occurs at an early epoch, when the protoplanetary disc was still massive, then rapid planet growth through accretion causes an otherwise stable disc to fragment into additional planetary mass bodies when the planetary mass reaches $4-5 m_{\rm Jupiter}$. We suggest that such catastrophic planet formation could account for apparent differences in the mass function of massive planets and brown dwarfs[1], and the existence of young stars that appear to have dissipated their discs at an early epoch[7]. Subsequent gravitational interactions[5,6,8,9] will lead to planetary systems comprising a small number of massive planets in eccentric orbits.

The planet–disc interaction has been studied extensively for low mass protoplanetary discs[3,10,11,12,13,14]. This is appropriate for the proto-Solar nebula where the rate limiting step, the assembly of the cores of the giant planets from smaller bodies[15], is believed to require timescales comparable to the lifetimes of protoplanetary discs, which are observed[7] to last for a few $\times 10^6 - 10^7$ yr. However, some extrasolar giant planets could form more rapidly, either via direct hydrodynamic collapse[16], or via accelerated core formation in discs that are significantly more massive[17] than the minimum mass Solar nebula[18]. More broadly, if angular momentum transport mechanisms other than self-gravity are inefficient in discs where the ionization fraction is low (and no purely hydrodynamic instabilities that lead to outward angular momentum transport are known to exist in Keplerian disc flows[19]), then the outer regions of protoplanetary discs may remain only marginally stable against gravitational instability even at *late* evolutionary epochs[20,21]. In either case, planet-disc interactions could occur while the effects of disc self-gravity are still important.

The local stability of a gaseous disc against gravitational instability depends upon the balance between thermal pressure and self-gravity. At a point in a disc with sound speed c_s, surface density Σ, and angular velocity Ω, the controlling parameter[22] is Toomre's Q, defined as,

$$Q = \frac{c_s \Omega}{\pi G \Sigma},$$

with G the gravitational constant. Numerical simulations[23,24] show that non-axisymmetric instabilities set in at $Q \lesssim 1.5$, and become increasingly violent for smaller values of $Q \approx 1$. We consider the relatively cool outer regions of the disc, at radii of several a.u., and set our initial conditions such that the disc is both marginally unstable, and has properties comparable to the upper end of the mass distribution of T Tauri discs inferred from mm wavelength observations[17], which have $m_{\rm disc} \approx 0.1 \ m_\odot$. This is around an order of magnitude greater than the canonical minimum mass Solar nebula value of $\sim 10^{-2} \ m_\odot$, though even for our Solar System the initial disc mass may have been substantially in excess of this minimum[25,26]. The surface density profile is taken to be

$$\Sigma = \Sigma_0 r^{-3/2} \left(1 - \sqrt{\frac{r_{\rm in}}{r}} \right),$$

where $r_{\rm in}$ is the inner edge of the simulated disc annulus. Σ_0 and c_s are chosen such that $m_{\rm disc} = 0.1$, and the ratio of disc scale height to radius at the outer edge is $(h/r) = 0.075$. With these parameters $Q > 1.5$ at all radii, and the disc is everywhere close to stable against gravitational instability, as expected if it is the endpoint of an earlier phase of violent gravitational instabilities that drive rapid angular momentum transport[21].

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[1]To appear in Nature, 9th December 1999.

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Figure 1 shows the evolution of the disc, computed using a Lagrangian hydrodynamics code. The isolated disc is shown at $t = 512$, in units where $\Delta t = 1$ corresponds to the dynamical time, Ω^{-1}, at $r_{\rm in}$. This run shows weak spiral arms in the outer disc, as expected from the Q profile on the basis of previous simulations of gravitationally unstable discs[23,24], and is amply stable against fragmentation. The disc surface density does not evolve significantly over this relatively short interval, as expected for a thin disc where the efficiency of angular momentum transport from gravitationally instabilities, if parameterized approximately via an equivalent Shakura-Sunyaev α parameter[27], corresponds to a fairly small effective $\alpha \sim 10^{-2}$.

We now consider the evolution of the same star-disc system with an embedded planet of initial mass $m_p = 10^{-3} m_*$. For seeds of this mass and smaller, the additional potential fluctuations induced by the planet at the Lindblad resonances[12] are small compared to the background fluctuations due to the disc's own self-gravity, as measured in the control run. This is shown in Figure 2. Neither the mass resolution nor the equation of state are realistic enough to model the internal structure of individual planets, so we focus solely on their influence on the disc, for which purpose details of their internal structure are unimportant.

The presence of a Jupiter mass planet significantly modifies the disc evolution. A partial gap is cleared in the disc on the dynamical timescale at r_p, bounded by a strongly compressed gravitational wake attached to the planet. This forms part of an $m = 2$ pattern of strong spiral arms, along with weaker transient spiral features excited in the disc by the combination of gravitational instability and planetary perturbation. The presence of a gap fails to prevent ongoing accretion along the spiral arms at a rate $\dot{m}_p \propto m_p$, with an e-folding time of a few planetary orbits. Continuing accretion is expected since the disc viscosity needs to be significantly lower than the values expected in a gravitationally unstable disc to inhibit accretion altogether[11]. Much of this mass accumulates in a resolved, strongly tidally distorted disc surrounding the planet. As the planet mass grows, the overdensity in the spiral arms and at the Lindblad resonances increases while the background surface density profile is unable to evolve on as rapid a timescale. This essential imbalance in timescales is expected to be valid even for the formation of giant planets in a minimum mass Solar nebula[26], and is therefore a robust prediction for the more massive discs studied here. The rapid growth in mass leads to an increased amplitude of potential fluctuations, as shown in Figure 2, decreasing disc stability, and inevitable fragmentation at the gap edges, shown in the lower panels of Figure 1. For these disc parameters and equation of state this occurs at $m_p = 4 - 5 \times 10^{-3} m_*$. Once this mass is reached, rapid fragmentation into numerous planetary mass bodies occurs near both the inner and outer Lindblad resonances.

Several additional calculations were used to check the sensitivity of the results to the initial conditions and numerical method. With the same initial conditions, fragmentation occurs at the same final planet mass in lower resolution simulations with 10,000 and 20,000 particles, though the initial masses of fragments do vary. In all cases, however, the fragments accrete rapidly from the disc, and so their final masses would fall into the regime of massive planets. Fragmentation also occurs at the same planet mass in a simulation where the initial seed mass was $m_p = 2 \times 10^{-4} m_*$, which is closer to the mass of a giant planet core beginning runaway accretion of disc gas[26]. For this simulation the time required prior to fragmentation was roughly doubled. Fragmentation does *not* occur if we artificially set the mass accreted by a Jupiter mass seed to zero, verifying that it is the increased planetary mass after significant accretion that leads to instability.

The existence of a propagating mode of planet formation has implications for the evolution of protoplanetary discs and the statistics of planetary systems. In particular, the formation of one massive planet could suffice to trigger rapid planet formation across the range of disc radii for which $Q \approx 1 - 2$. This could allow massive planets to form at large radii where the timescales for planet formation via other mechanisms can become worryingly long compared to typical disc lifetimes. The consequent disruption of the outer disc concomitant with such violent planet formation would allow the unreplenished inner disc to drain viscously onto the star in a short timescale. Studies of the UV and Hα flux arising from the accretion process, and near infra-red flux from the inner disc, suggest that a significant fraction of T Tauri stars are able to dissipate their inner discs rapidly[7]. Related processes may be relevant to the formation of planetary satellite systems[12].

For planetary formation, these results imply that steady growth of giant planets in massive discs around solar mass stars is limited by the vulnerability of the disc to fragmentation once the planetary mass reaches approximately $5 m_{\rm Jupiter}$. The resulting formation of additional planets, which then compete to accrete the available disc gas, implies an upper limit to the mass of massive planets formed via this mechanism. In particular, even if the disc was sufficiently massive it would not be possible to grow a planet from a Jupiter mass far into the brown dwarf regime. This is consistent with observational evidence that planets and brown dwarfs do not share a common mass function[1], which has prompted suggestions that a break in formation mechanisms exists at around $7m_{\rm Jupiter}$. Finally we note that the endpoint of early disc fragmentation would be a system of numerous massive coplanar planets in initially close to circular orbits. Such a system would possess a global organisation imprinted via non-local gravitational effects at birth. The subsequent evolution will be strongly affected by mutual perturbations. These would be favourable initial conditions for the eventual formation of a system comprising one or more massive planets on eccentric orbits[9].

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ACKNOWLEDGEMENTS. We thank Norm Murray for many helpful discussions, and Norman Wilson for maintaining the required computational resources.

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